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Adaptive spectral imager for space-based sensing

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ABSTRACT

Optical sensors aboard space vehicles designated to perform seeker functions need to generate multispectral images in the mid-wave infrared (MWIR) and long-wave infrared (LWIR) spectral regions in order to investigate and classify man-made space objects, and to distinguish them relative to the interfering scene clutter. The spectral imager part of the sensor collects spectral signatures of the observed objects in order to extract information on surface emissivity and target temperature, both important parameters for object-discrimination algorithms. The Adaptive Spectral Imager described in this paper fulfills two functions simultaneously: one output produces instantaneous two-dimensional polychromatic imagery for object acquisition and tracking, while the other output produces multispectral images for object discrimination and classification. The spectral and temporal resolution of the data produced by the spectral imager are adjustable in real time, making it possible to achieve optimum tradeoff between different sensing functions to match dynamic monitoring requirements during a mission. The system has high optical collection efficiency, with output data rates limited only by the readout speed of the detector array. The instrument has no macro-scale moving parts, and can be built in a robust, small-volume and lightweight package, suitable for integration with space vehicles. The technology is also applicable to multispectral imaging applications in diverse areas such as surveillance, agriculture, process control, and biomedical imaging, and can be adapted for use in any spectral domain from the ultraviolet (UV) to the LWIR region.

Keywords: Multispectral, hyperspectral, imaging, infrared, space vehicle

1. INTRODUCTION

Future optical sensors aboard space vehicles will, in addition to other functions, need to investigate and classify other man-made objects within their field of view, and to distinguish them against the interfering scene clutter (e.g. contribution from Earth radiation and light reflection). This need can be fulfilled by generating and analyzing multispectral/hyperspectral images of those objects. The Adaptive Spectral Imager described in this paper produces instantaneous two-dimensional polychromatic (spectrally unresolved) imagery for object acquisition and tracking, and, simultaneously, multispectral images for object discrimination and classification. By using the mid-wave infrared (MWIR) and long-wave infrared (LWIR) spectral signatures of the object, it is possible to extract the information on object temperature and surface material, for objects showing significant temperature contrast relative to the surrounding scene.

The spectral and temporal resolution of the data produced by the spectral imager are adjustable in real time, making it possible to achieve the optimum tradeoff between different sensing functions in order to meet the dynamic monitoring requirements of this application. The system needs to produce near-diffraction limited imagery with as high optical collection efficiency as possible, and with a provision for spectral multiplexing (collecting data on many wavelengths simultaneously). The instrument should be designed as a robust, small-volume, lightweight and low-power consumption device with no macro-scale moving parts in order to make it suitable for integration into space vehicles.

In this paper we describe the design of the Adaptive Imaging Spectrometer, the results of performance modeling, the unique optical system of the instrument and the results of the experimental work with a feasibility demonstration prototype.

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2. INSTRUMENT CONCEPT

The principles of operation of the Adaptive Imaging Spectrometer are illustrated on Fig. 1. The instrument uses two polychromators (or a single polychromator in two passes) and a spatial light modulator (SLM) placed between them. There is no physical slit in the system; the system operates as a staring two-dimensional (2D) imaging device. The first polychromator disperses and images all spectral components onto the SLM. The SLM spectrally encodes the image by modulating the intensity of selected spectral bands in the dispersed image. This operation is equivalent to applying a mathematical transform to the spectrally resolved image, and is easy to do with a digitally controlled SLM. The encoded image is spectrally recombined by the second polychromator and imaged onto a 2D focal plane array (FPA) photodetector (Fig. 1).

Spectral encoding is achieved by transmission, rejection or intensity modulation of particular wavelengths. A 2D array SLM whose pixels are individually addressable (and small relative to the resolution element), can be programmed to generate a dynamic series of spatial patterns (masks) that implement a variety of transform functions. Transform functions include traditional single-slit wavelength scanning, simple multiple-slit filtering, multiplexed Hadamard transform spectroscopy, and "matched filter" transform, where the SLM is used to produce a spectral mask that matches known distinctive spectral features of the target. An approach even more advanced is to construct a "filter" mask over the SLM that mimics the multivariate regression vector for a specific principal component. In this way, the optical processing by the SLM becomes equivalent to numerically projecting the input spectrum onto the principal component chosen by the SLM mask. The detector signal then becomes the "score" of the measured spectrum relative to a selected principal component. A number of principal components can be investigated in quick succession, by cycling their respective multivariate regression vector masks over the SLM.

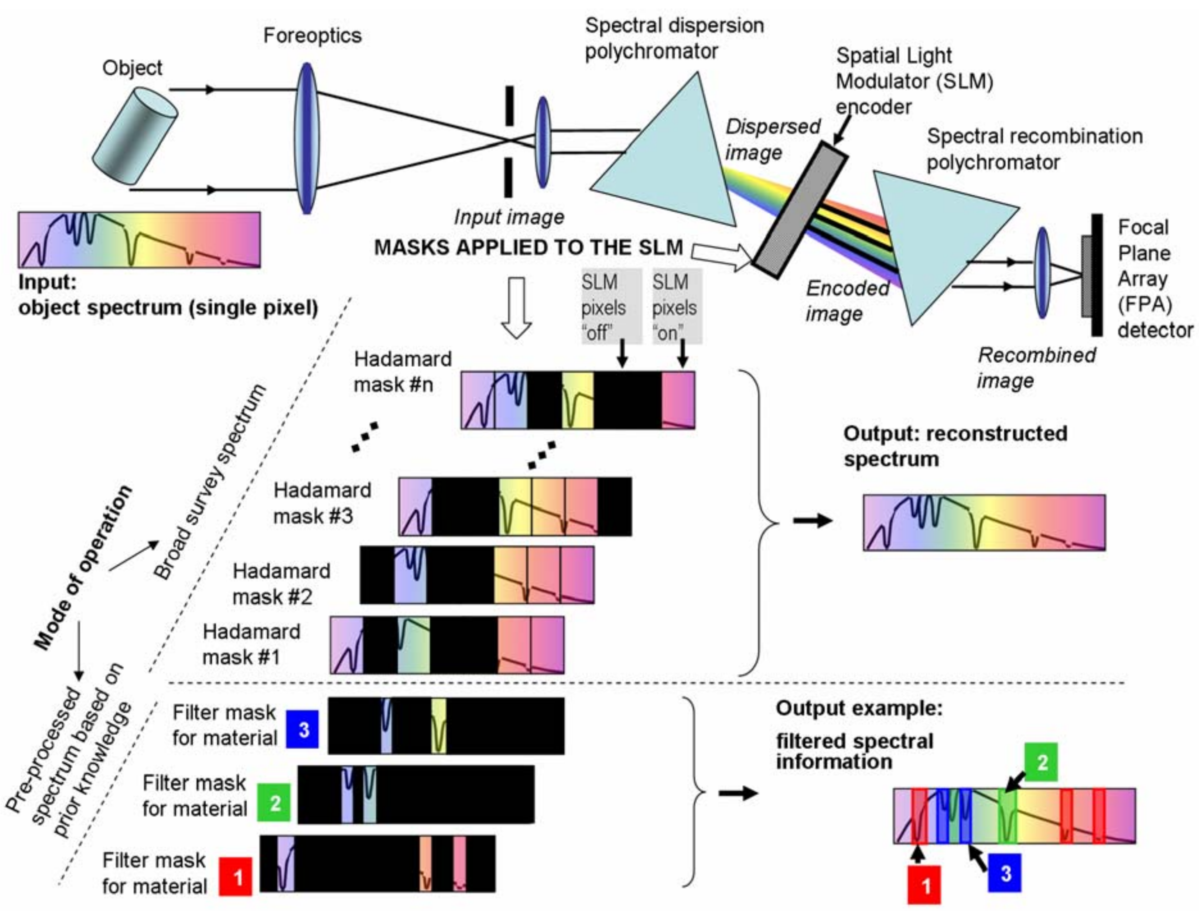

Figure 1: Principles of operation.

The Adaptive Spectral Imager described here uses a reflective Digital Micromirror Array (DMA) as the modulator that performs spectral encoding of two-dimensional images. For the case where remote measurement of temperature and emissivity of the object is the main goal, the spectrometer operates in the MWIR/LWIR range, and typically acquires broadband spectra in a “survey” (not filtered) mode (Fig. 1). Such mode of operation is best implemented by the Hadamard transform due to its multiplexing capability and its processing speed[1]. For Hadamard transform, the DMA is programmed with a series of binary masks based on Simplex (S) matrices, where elements 0 and 1 translate into on-off modulation of individual micromirror pixels of the DMA[1]. Recording a N-channel spectrum in this way requires N masks based on a set of N matrices resulting in $N^{1/2}/2$ multiplex (Felgett’s) advantage in the signal to noise ratio (SNR) relative to the slit-scanning approach. The multiplexing approach collects the light contained in approximately half of all the wavelengths simultaneously at any point in time, thereby providing the much needed photon collection efficiency in the MWIR/LWIR. The recorded images are decoded by the inverse Hadamard transform to provide the spectrum for each individual pixel (Fig. 1).

3. INSTRUMENT DESIGN

The Adaptive Spectral Imager for space vehicles relies on dedicated foreoptics (typically a telescope) to deliver the image into its input field (Fig. 2). It also uses one or more 2D detector arrays (FPA) to convert the photons into electrical signals that can be further processed by the sensor’s electronics and analyzed by onboard computers (Fig. 2).

The imager provides data for two functions simultaneously, based on the way the output from the FPA is processed: one output produces standard unresolved polychromatic images at the maximum frame rate of the FPA, which the space vehicle can use for object acquisition and tracking. The other output, processed simultaneously with the first one produces multispectral images for object discrimination and classification. By applying selected functions with a selected set of parameters to the spectral modulator, the type of information and spectral and temporal resolution of the data produced by the spectrometer can be adjusted in real time (Figs. 1 and 2).

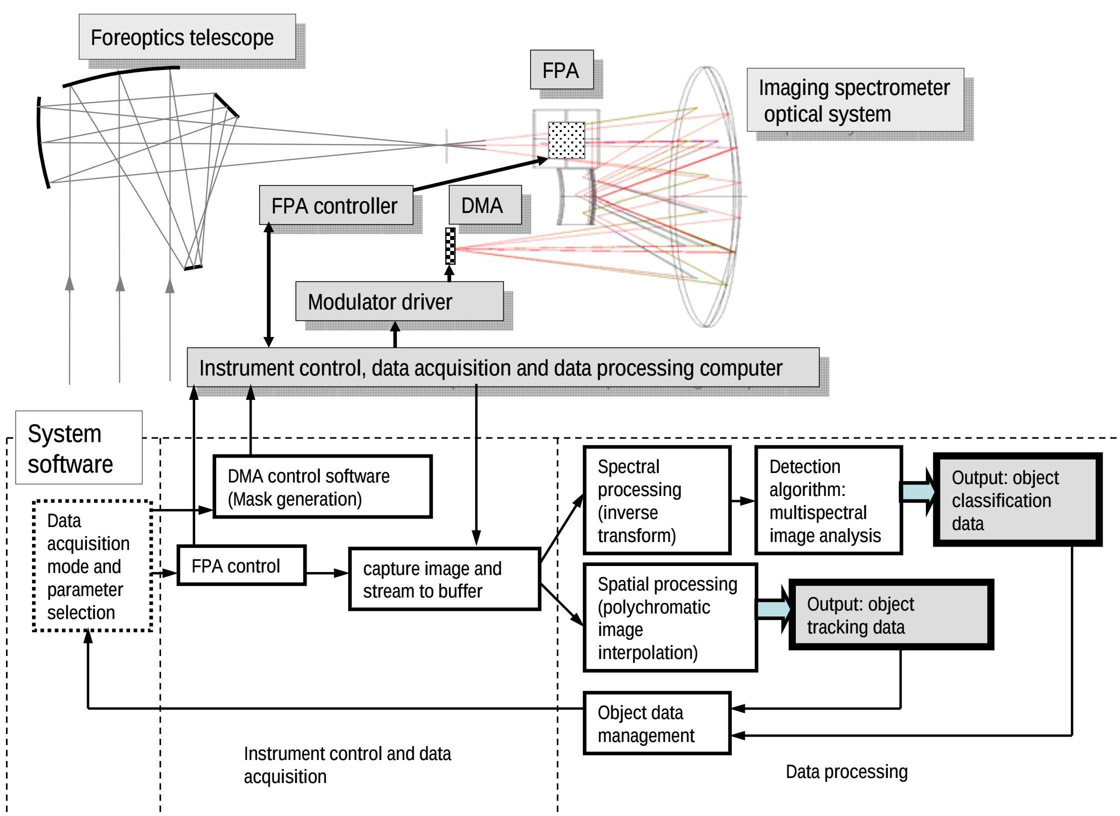

Figure 2: System design.

The conceptual block diagram of the software package that controls the instrument, collects data, and delivers spatial and spectral information to higher-level external programs is presented on Fig. 2. The data stream captured by the FPA is routed to parallel spatial and spectral processing. The spatial image is based on the integrated intensity of all open spectral channels (about half of the total for the Hadamard transform). In order to make this image equivalent as much as possible to the panchromatic image that would be captured by a staring FPA, additional simple processing can be applied in the form of interpolation and fitting pixel intensities. The output of this procedure is high quality two-dimensional imagery used in real time by the target-tracking subsystem of the vehicle.

In the case of collecting broad spectra with the Hadamard transform-based modulation, the spectral processing software starts with pixel-by-pixel processing of the data. The reduction of Hadamard encodegrams into spectra is accomplished by applying the inverse Hadamard transform[1]. While this operation in a general case could be rather time-consuming, due to the large number of matrix inversions involved, the inversion of binary square cyclic S-matrices is extremely efficient and fast (orders of magnitude faster than e.g. Fast Fourier Transform (FFT) calculations). The resulting datacubes are arranged in a band-sequential format, standard for processing multispectral and hyperspectral imagery. In the case of temperature/emissivity measurements, based on multichannel infrared spectrothermometry, the Planck function is fitted to the data with great accuracy, due to a large number of channels (10-100) in a wide spectral range (entire MWIR or LWIR region, or both). Such rich spectral information makes it possible to successfully unmix the temperature and the emissivity of the object, thereby providing data on the nature of the radiating surface. Additionally, the abundance of spectral data also helps separate the target signature from other, often complex and confounding optical phenomena seen by the sensor, which can easily contaminate the target's spectral signature.

The Adaptive Imaging Spectrometer must be able to detect small objects at great distances, meaning that the object image might be smaller than a single pixel on the FPA and very faint. Therefore, the optical system needs to be both near-diffraction limited and have a large collection efficiency. As described above related to Fig. 1, two high quality polychromators are needed, in a back-to-back configuration, making the optical design not a simple task, especially under the size and weight constraints of space based instrument. Candidate spectrometer layouts for such a system can be based either on a pair of Offner spectrometers with discrete elements[2,3], a pair of curved-prism spectrometers[4], or a design based on an integrated double Offner relay, where elements are shared between the dispersion and the recombination paths. We have analyzed the first two options and found them mechanically complex and bulky for a space-based instrument. Therefore, we have embarked on a task to design a dedicated optimized optical system for adaptive spectrometers, based on the third option (Fig. 3).

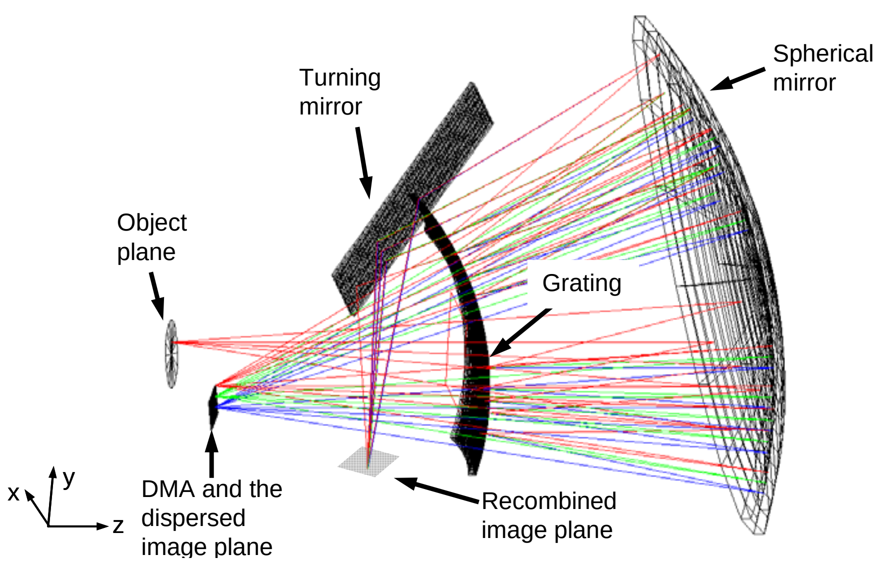

Figure 3: Double-pass adaptive imaging spectrometer: solid model.

The optical system of Fig. 3 uses a novel and simple dual-pass spectrograph design, defined by two curved elements, a grating and a single spherical reflector. The spectrograph uses a near-concentric configuration, similar to the Offner relay[2]. Like all Offner spectrographs, it uses a curved grating with a radius of curvature of one-half that of the spherical mirror to produce a dispersed image with 1:1 magnification. The input and output images are located in a plane containing the center of curvature, but displaced from the center of curvature. The design differs from the traditional design in that it uses a vertical rather than lateral orientation of the grating, meaning that the light is dispersed in a direction perpendicular to the image displacement. This places the dispersed image near the center of curvature in the dispersion plane, thereby minimizing the image aberrations. By contrast, other designs using the lateral orientation[3], disperse the light along the displacement direction. This results in very good imaging in the slit dimension, but large image aberrations in the direction perpendicular to the slit. While a dual-pass spectrograph can be made by combining two lateral Offner spectrographs[5,6], a much higher level of complexity is required. We have found that we can achieve near-diffraction limited image quality with just two curved surfaces using the vertical configuration. By contrast, six curved surfaces (two gratings and three spherical reflectors) are required to achieve the same image quality with the lateral configuration.

We are currently assembling a breadboard prototype of the dual-pass spectrograph for testing. Figs. 3 and 4 show a solid model and a plane view of the optical system, respectively. The spectrograph is defined by the grating and the spherical mirror. The input and output of the spectrograph are displaced from the center of curvature along the X-axis, and the light is dispersed along the Y Axis. The light makes two complete passes through the relay, once to disperse the light, once to recombine the light. Light entering the spectrograph at the object plane passes through the spectrograph to form a dispersed image on the DMA. The DMA reflects the input light at a 24-degree angle in the YZ plane and passes it back through the spectrograph, which recombines the various wavelengths. A turning mirror picks off the light returning light and forms a recombined image on the detector. Without the turning mirror, the recombined image would overlap the input image in the object plane.

For convenience in testing, we are using relatively large optics and a standard camera dewar. The concave mirror has a diameter of 180mm and a radius of curvature of 200mm. The grating is a 19mm x 45mm convex rectangle, with the radius of curvature of 100 mm. The effective F-number of the system is F/2.8. The modulator is a rectangle of 14x10.5mm, rotated 45 degrees about the Z-axis. The wavelength range is 7-13μm in the first order, 3.5μm- 5μm (6.5μm) in the second. The FPA is a liquid nitrogen cooled array of 256x256 square pixels of 30μm x 30μm each (8mm x 8mm total size). The recombined image is nearly-diffraction limited. The geometric spot size radii are between 10 and 20 μm rms, over the entire 8 x 8 mm field of view.

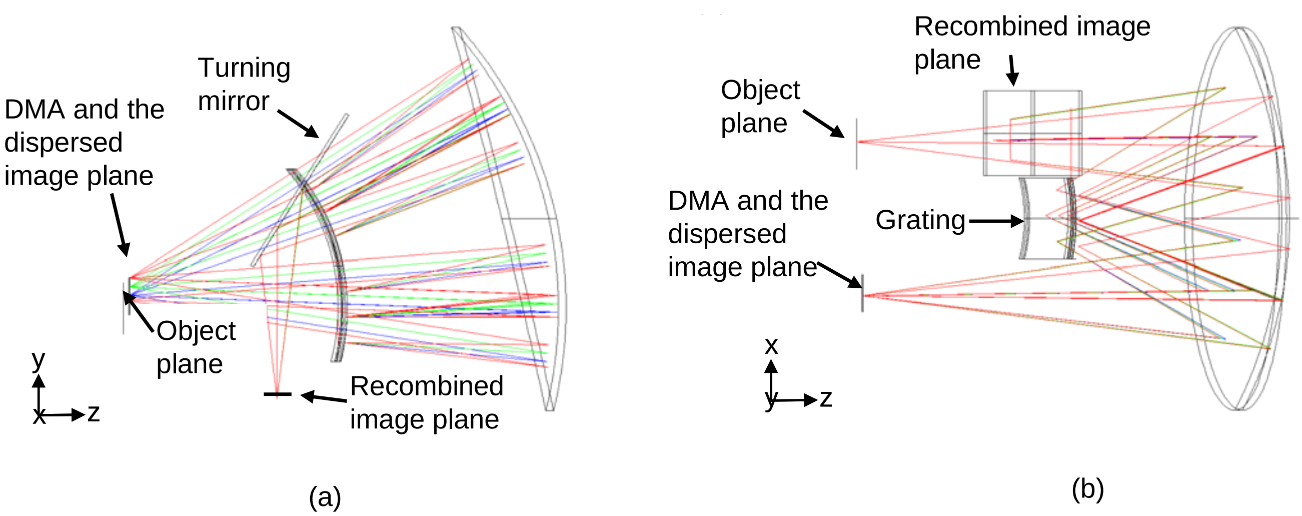

Figure 4: Double-pass adaptive imaging spectrometer optics: plane view in the dispersion plane YZ (a) and in the offset plane XZ (b).

The spatial light modulator used in our system is a modified DMA chip by Texas Instruments (DMD 0.7 XGA 12° DDR). The array consists of 1024 x 768 aluminum coated individual micromirrors of 14μm x 14μm each, capable of ±12° tilt relative to the diagonal. Mirrors are individually addressable through a driver circuit available from the manufacturer. Modulation bandwidth close to 10kHz is possible with a high speed version of the driver circuitry. For IR applications, the original glass window needs to be replaced with a ZnSe IR-transparent window.

The size of individual micromirrors for the TI DMA chip has been chosen to produce negligible diffraction effects in the visible range, where the chip is typically used. However, at long 7μm -13μm wavelengths used here, the diffraction effects can seriously degrade the optical performance, if an optical system with a small collection angle is used. We have modeled the diffraction effects within a system of the kind presented on Fig. 3 in the range 3μm-13μm and found a strong dependence of the image quality on the collection angle of the optics. However, the model shows the collection angle afforded by F/2.8 of the system of Fig. 3 is large enough to produce the intensity ripples in the recombined focal plane not larger than several percent of the maximum intensity.

Assuming that the image generated on the FPA fills a detector pixel (this corresponds to the spatial resolution of 0.5m at the distance of 100km), with F/2.8 optics, the spectral resolution of 10 channels, and a typical LWIR FPA sensitivity radiometric calculations for our LWIR adaptive spectral imager suggest the signal-to-noise ratio (SNR) around 28dB per collected spectrum, which is high enough to accomplish object characterization.

4. EXPERIMENTAL MODEL

A feasibility prototype of the Adaptive Spectral Imager as applied to standoff imaging thermography has been demonstrated so far in the VIS/NIR spectral region 600nm – 1100nm where a silicon CCD camera was used. Such system is aimed at imaging thermography of objects at temperatures above 1000K. An optical system based on refractive and transmissive components was assembled for the purpose. Data acquisition and processing software was developed for the control of the DMA, capturing data from the CCD camera, and for data reduction. Spectral calibration with known input wavelength(s) produced the instrument calibration factor of 0.41nm per micromirror of the DMA array.

The imaging thermography capability of the prototype was investigated by using three blackbody objects at different temperatures placed into the instrument's field of view (Fig. 5). The blackbodies were represented by electrically heated resistors kept at constant temperature. One of the sources used (Object 1, Fig. 5) was a calibrated 1250K blackbody source. A seven-element Hadamard mask was used to produce seven-band spectra of each object with adequate spectral resolution for temperature measurement at a fast update rate. Fig. 5 shows a dynamic sequence of data collected with our adaptive spectral imager. The left-hand side shows the time sequence of spatial (spectrally combined) images, as generated after each Hadamard transform mask was applied to the DMA. Since half of all the spectral channels are open at any moment in time, and since the FPA readout is updated after every mask, the spectrally recombined image on the FPA shows a near-panchromatic view of the objects. The right-hand side of Fig. 5 shows the raw (instrument function included) Hadamard-decoded spectra of three objects, updated partially after each mask, and updated fully after each complete cycle of 7 masks. Data are scaled by an approximate instrument function, to compensate for the detector falloff at wavelengths greater than 900 nm. Figure 6 shows the same data along with a fit to the Planck function that reveals the approximate temperature of the object. Note that the vertical (signal intensity) scale does not represent the radiance of the object, since the solid angle has not been calibrated. Based on this approach we found the approximate temperatures of the three objects to be 1400K, 1600K and 1900K (Fig. 6).

After experimentally demonstrating the ability to perform imaging thermography of high-temperature objects in the VIS/NIR spectral region with the simple demonstration experiment described, we have focused at building a much more technologically complex MWIR/LWIR system described above. The system will be capable of imaging thermography at temperatures around and above 300K. The system, which is based on the design described in Section 3 above, is currently under construction.

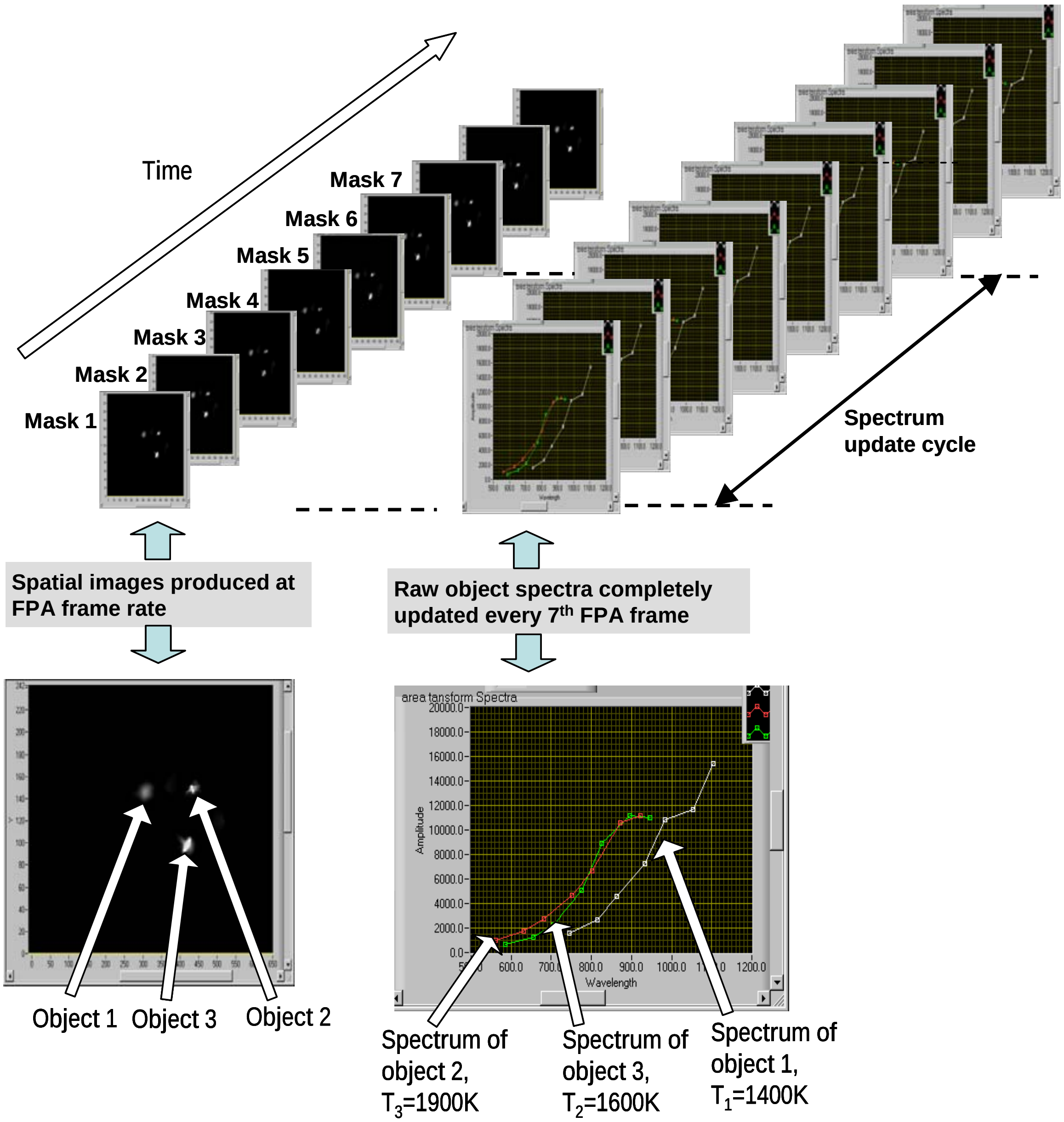

Figure 5: Data acquisition dynamics for adaptive imaging spectrometer as demonstrated by spectral imaging objects at different temperatures within the field of view of the instrument.

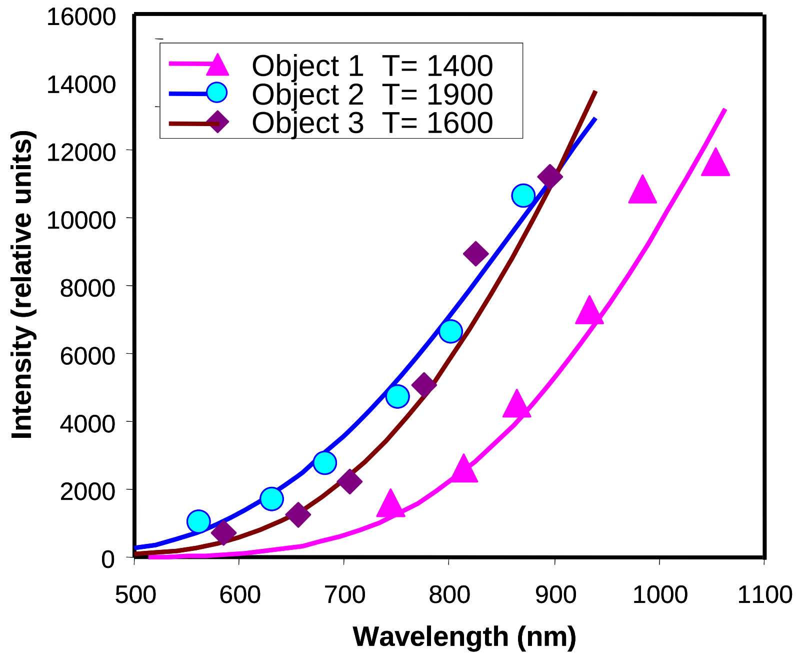

Figure 6: The spectra of three objects in the field of view of the imaging spectrometer, together with blackbody curves fitted to the temperatures indicated.

5. CONCLUSIONS

A multispectral imager designed to simultaneously produce broadband two-dimensional imagery for target tracking, and multispectral images for target discrimination is described. Under software control, the imager can perform a variety of spectral transforms with real-time variable data acquisition parameters. Fast adaptive spectral imagers based on this approach can greatly improve the discrimination function of space based optical sensors by allowing real-time optimization between the information content and the data rate. The instrument's hardware architecture is favorable for space applications, since it contains no macro-scale moving parts and can be built in a robust, small-volume and low-mass package. The technology is also applicable to multispectral/hyperspectral imaging applications in diverse areas such as surveillance, atmospheric remote sensing, process control and biomedical imaging, and can be adapted for use in any spectral domain from the ultraviolet (UV) to the LWIR region.

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